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14. ABSTRACT
We conducted experimental investigations and formulated mathematical theories of human coordination over networks with information constraints. The human population was modeled as agents that could make constrained decisions in a distributed coordination game scenario. In our experiments agents could only communicate and interact over a network. We designed different coordination algorithms inspired by laboratory experiments and evaluated their performance. We also investigated the notions of common knowledge and how this leads to strategic decision making and state dependent equilibria in networks. Finally, we started the investigation of the

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Report Title

Final Report: Algorithmic Modeling of Social Interactions Over Networks

ABSTRACT

We conducted experimental investigations and formulated mathematical theories of human coordination over networks with information constraints. The human population was modeled as agents that could make constrained decisions in a distributed coordination game scenario. In our experiments agents could only communicate and interact over a network. We designed different coordination algorithms inspired by laboratory experiments and evaluated their performance. We also investigated the notions of common knowledge and how this leads to strategic decision making and state dependent equilibria in networks. Finally, we started the investigation of the spread of emotions over social networks using large data sets from on-line social media.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
09/03/2015	10.00	Yunkyu Sohn, Adam D. I. Kramer, Cameron Marlow, Lorenzo Coviello, Massimo Franceschetti, Nicholas A. Christakis, James H. Fowler. Detecting Emotional Contagion in Massive Social Networks, PLoS ONE, (03 2014): 0. doi: 10.1371/journal.pone.0090315
09/03/2015	11.00	Lorenzo Coviello, Massimo Franceschetti. An instance of distributed social computation: the multi-agent group membership problem, IEEE Transactions on Control of Network Systems, (01 2014): 0. doi: 10.1109/TCNS.2015.2453671
10/05/2012	3.00	Lorenzo Coviello, Massimo Franceschetti, Mathew McCubbins, Ramamohan Paturi, Andrea Vattani. Human matching behavior in social networks: an algorithmic perspective, PLoS ONE, (08 2012): 1. doi:
TOTAL:		**3**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
TOTAL:		

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper	
07/23/2012	2.00	Massimo Franceschetti, Lorenzo Coviello. Distributed team formation in multi-agent systems:stability and approximation, IEEE Conference on Decision and Control (IEEE-CDC). 12-OCT-12, . : ,
09/12/2013	5.00	Nuh Aygun Dalkiran , Moshe Hoffman , Ramamohan Paturi , Daniel Ricketts , Andrea Vattani. Common Knowledge and State-dependent Equilibria,, 5th International Symposium on Algorithmic Game Theory, Barcelona, Spain, 2012.. 22-OCT-12, . : ,

TOTAL: **2**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
09/12/2013	7.00	Lorenzo Coviello, Massimo Franceschetti. An instance of distributed social computation:the multi-agent group formation problem, SUBMITTED (08 2013)
09/12/2013	8.00	Massimo Franceschetti, Lorenzo Coviello. Matching markets with bundle discounts:computating efficient, stable and fair solutions, SUBMITTED (08 2013)
09/12/2013	9.00	Lorenzo Coviello, , Yunkyu Sohn, , Adam D. I. Kramer, , Cameron Marlow, , Massimo Franceschetti, , Nicholas A. Christakis, , James H. Fowler . Detecting emotional contagion in massive social networks, SUBMITTED (08 2013)
10/05/2012	4.00	Nuh Aygun Dalkiran, , Moshe Hoffman, , Ramamohan Paturi, , Daniel Ricketts3, , Andrea Vattan. Common knowledge and state dependent equilibria, Preprint (07 2012)
TOTAL:		**4**

Number of Manuscripts:

Books

Received		Book
TOTAL:		

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Massimo Franceschetti received the 2012 Antonio Ruberti Young Researcher Prize (under 40 years of age) from the IEEE Control Systems Society

Ramamohan Paturi received the 2013 Nerode Prize for outstanding papers in the area of multivariate algorithmics.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
David Moeller	0.13	
Andrea Vattani	0.03	
Lorenzo Coviello	0.24	
FTE Equivalent:	**0.40**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Massimo Franceschetti	0.08	No
Ramamohan Paturi	0.09	
FTE Equivalent:	**0.17**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Matthew Jacob Jones	0.01	Computer Science Eningeering
FTE Equivalent:	**0.01**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	1.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Lorenzo Coviello
Andrea Vattani
Daniel Moeller
Total Number: 3

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

"Algorithmic Modeling of Social Interactions Over Networks"
ARO Project W911NF1110363
08/15/2011 to 08/14/2014
FINAL REPORT

1 Statement of the problems studied

We have conducted experimental and theoretical studies of human behavior over social networks, considering different canonical problems of interest related to network equilibria under different information constraints. The main topics studied were:

1. Formation of stable matchings over networks of social contacts.
2. Stable and fair solutions in matching markets with incentives.
3. Distributed team formation over human networks.
4. Common knowledge formation and state dependent equilibria.

All problems relate to the common theme of distributed coordination of human agents over networks of social contacts. We developed both an algorithmic mathematical theory, and performed experiments with real data. The common theme of this research was to reveal how mathematical tools, including probability theory, can be used to predict human behavior under different information-limited scenarios.

The first problem concerns stable matchings, a natural scenario in which actors and resources (for example, candidates and jobs, residents and hospitals) are paired with each other. The stable matching problem also has many applications to real world markets and efficient centralized algorithms are known. However, little is known about the decentralized case. Several natural randomized algorithmic models for this setting have been proposed but they have worst case exponential time in expectation. We presented a novel structure associated with a stable matching on a matching market. Using this structure, we were able to provide an analysis of the complexity of a subclass of decentralized matching markets. Our central contribution was to provide analytical tools that can explain why some markets seem to work in practice efficiently (fast convergence is taken as a measure of efficiency). At the technical level, we introduced

new concepts such as Jealousy graphs and generalizes the notion of correlation. We have also considered the computational problem resulting from a distributed game scenario in which, given a network where nodes represent human subjects and edges represent social contacts, the group objective is to pair nodes in such a way that the largest number of matched pairs is formed. The solution must be achieved in a distributed fashion using only limited communication among nodes that share links. The investigation of this problem was started during the performance period of the previous seed (STIR) grant. We continued the investigation and published one journal paper on the topic.

The second problem also concerns matching, but this time in the context of markets. We modeled a matching market in which nonstrategic vendors sell items of two types at fixed prices, but offer a discounted price on the bundle of both items based on demand volumes. Each buyer acts strategically in order to maximize her utility, given by the difference between product valuations and price paid. In a market with transferable utility, buyers might be willing to cooperate by exchanging sidepayments, to induce discounts. For this model, we proposed an algorithm to compute efficient matchings that is polynomial in the number of players, by conditioning on the number of buyers matched to each pair of vendors, and improving upon a natural formulation of the problem as a integer program whose relaxation is not guaranteed to have integral solutions.

Generalizing the matching problem to team formation, in our third problem we considered a scenario in which leaders are required to recruit teams of followers. Each leader cannot recruit all followers, but interaction is constrained according to a bipartite network. The objective is to reach a stable state in which each follower is part of a team, and each leader controls a team whose size satisfies a given constraint. We focused on distributed strategies, in which agents have only local information of the network topology and propose a distributed algorithm in which leaders and followers act according to simple local rules. The performance of the algorithm is analyzed with respect to the convergence to a stable solution. In this case, we performed a theoretical analysis and experiments on real human networks. The theoretical model was developed using the results of the matching game as a first guideline.

We used a computer interface where subjects that shared links could interact between each other using a graphical point-and-click interface. In this way, they could propose to match with a current neighbor, accept a proposal, or break a matching in which they are currently participating. We performed experiments using this interface using a diverse population of undergraduate students as subjects (having obtained IRB and ARO-HRPO approval). Based on these results we have built a mathematical model for the algorithmic behavior of subjects and tested this model with additional experimental data. The model provided insights into the convergence properties and the ability of humans to solve coordination tasks over a network.

Our last problem can be described as follows. Many puzzling social behaviors, such as avoiding eye contact, using innuendos, and insignificant events that trigger revolutions, seem to relate to common knowledge and coordination, but the exact relationship has yet to be formalized. Herein, we present such

a formalization. We state necessary and sufficient conditions for what we call state-dependent equilibria equilibria where players play different strategies in different states of the world. In particular, if everybody behaves a certain way (e.g. does not revolt) in the usual state of the world, then in order for players to be able to behave a different way (e.g. revolt) in another state of the world, it is both necessary and sufficient for it to be common p-believed that it is not the usual state of the world, where common p-belief is a relaxation of common knowledge introduced by Monderer and Samet. Our framework applies to many player r-coordination games a generalization of coordination games that we introduce and common (r; p)-beliefs a generalization of common p-beliefs that we introduce. We then apply these theorems to two particular signaling structures to obtain novel results. Results have been submitted to a journal for publication and are currently under review.

The results related to the problems described above appeared in the following papers:

- Nuh Aygun Dalkiran, Moshe Hoffman, Ramamohan Paturi, Daniel Ricketts, and Andrea Vattani. Common Knowledge and State-dependent Equilibria, Proceedings of SAGT 2012 (Symposium on Algorithmic Game Theory 2012), Barcelona, Spain.

- L.Coviello, M. Franceschetti, M. D. McCubbins, R. Paturi, A. Vattani "Human matching behavior in social networks: and algorithmic perspective." PLoS One, 7(8), e41900, August 2012.

- L. Coviello, M. Franceschetti. "An instance of distributed social computation: the multi-agent group membership problem." *IEEE Trans. on Control of Network Systems*, 99(1), to appear 2015. Conference version appeared in IEEE-CDC 2012.

- M. Hoffman, D. Moeller, R. Paturi Jealousy Graphs: Structure and Complexity of Decentralized Stable Matching, which is being reviewed by Proceedings of the 9th International Conference on Web and Internet Economics: (WINE 2013).

- L.Coviello, Y. Sohn, A. Kramer, C. Marlow, M. Franceschetti, N.A. Christakis, J.H. Fowler "Detecting emotional contagion in massive social networks." PLoS One, 9(3), e90315, March 2014.

- L.Coviello, M. Franceschetti. "Matching markets with bundle discounts: computing efficient, stable, and fair solutions." Under submission.

2 Main Contributions

For which concerns the matching problem, from the experimental data, we were able to identify an invariant decisional property called "prudence" which is related to the well known concept of risk aversion in economics. According to this

property, subjects tend to not break their current matching, unless they have a pending proposal from another subject. Based on this property, we formulated a randomized algorithm to model humans behavior and analyzed its complexity and performance over a wide range of graphs. This algorithm is shown to closely track the real human behavior. It is also "human like" in the sense that it is run with minimum memory and communication requirements. The results from the analysis of the algorithm show that humans are generally successful in solving the matching game approximately, but there exist specific instances of the problem where they have trouble in finding an exact solution. This somehow vague statement is cast into a rigorous framework using mathematical analysis of the convergence properties of the algorithm and is validated using experimental data. A detailed description appears in the PLOS-ONE journal paper. Our results show that the algorithmic approach is a promising one in the analysis of human behavior over networks and we plan to extend the investigation in the future to other coordination problems that could better model real scenarios.

Regarding the team formation problem, our results are as follows. We developed a human like algorithm for team formation that is inspired from previous results on matching. This algorithm is simple, it has minimal memory requirements, runs completely distributed, and models human behavior (although thsi last statement needs to be verified using experiments on real subjects). For any network, the proposed algorithm is shown to converge to an approximate solution in polynomial time, namely the leaders quickly form teams in which the total number of additional followers required to satisfy all team size constraints is an arbitrarily small fraction of the entire population. When the maximum degree of the leaders is constant in the network size, a stable solution that satisfies all team size constraints is found in polynomial time. In contrast, for general graphs there can be an exponential time gap between convergence to an approximate solution and to a stable solution. Our preliminary results will be validated using experimental data and represent a first step in understanding human behavior in complex coordination tasks. They can also be useful for robotic networks in coordinating agent systems.

Regarding common knowledge, we introduced state-dependent equilibria, which we define as equilibrium strategies in which players take different actions when the circumstances change. This notion allows us to address the questions that were left unanswered by the informal discussions of common knowledge and coordination. In particular, we characterize the conditions under which rational players are able to play state-dependent equilibria. One of our main results shows that it is not common knowledge that determines the existence of state-dependent equilibria but rather a relaxation of common knowledge. Previous works of other authors have argued that common knowledge is important for coordination. For example, it arises in a number of common political situations in which the populace knows the current regime is inept but takes no action against it until some seemingly insignificant event occurs, such as the street vendor in Tunisia who set himself on fire leading citizens to rise up in protest. However, without formal arguments, many important questions still remained. Our work is a first step in providing a more rigorous framework to describe this

phenomenon.

Events that do not directly affect fundamental payoffs may nevertheless impact economic outcomes. Such events, typically called *sunspots*, derive influence from their ability to coordinate beliefs and agent behavior. While sunspot equilibria have been applied in macroeconomic and other contexts, the foundations of sunspots are not well-understood. We are building a general, unified game-theoretic framework that characterizes when and how sunspot equilibria can arise. Our first work investigated necessary and sufficient conditions for the existence of sunspot equilibria under general information structures. Our current project investigates what types of events can act as sunspot equilibria.

These two sets of results provide simple insights into how payoff-irrelevant events can influence play in coordination games: Our first result shows that if an event does not create *common knowledge*whenever the event occurs, everyone knows the event has occurred, and everyone knows that everyone knows the event has occurred and –the event cannot act as a sunspot to coordinate play. This observation suggests an explanation for indirect speech like innuendo. Indeed, innuendos by nature impact first-order knowledge, but leave higher-order knowledge uncertain – even if the a recipient understands an innuendo, the sender may think that the recipient does not, and even if the sender thinks the recipient does understand, it is likely that the recipient thinks the sender thinks he does not. Thus, in contrast to explicit speech, innuendos do not lead to common knowledge events. Consequently, innuendos communicate first-order information without affecting player coordination. Our second result, which characterizes potential sunspots, provides a possible explanation for symbolic gestures, such as bowing or shaking hands: These events, provided that they have the appropriate common knowledge property, can re-coordinate behavior in a game with multiple equilibria.

These results have prescriptive implications. For example, if one wants to market a new technology – especially one that has a coordination component, like a standard – it is crucial to make explicit the benefits of the technology to a broad population. A subtle marketing campaign may communicate the technology's individual-level value without enabling consumers to coordinate on adoption.

3 Relevance to DOD

Our results contributed to the understanding of the dynamics of complex human systems. Team formation and matching are important topics in distributed organizations, including tactical deployments. We have demonstrated that an algorithmic approach in modeling distributed agents can be successful to predict global equilibria. In particular, we showed the power of reduction of complex interactions to simple elementary actions performed with limited communications. This reduction can lead to efficient computational models while retaining the predicting power. Our studies on common knowledge improved understanding of the mechanisms underlying triggering of global phenomena. Our study

is a first step towards the understanding of social dynamics work, and how to predict and regulate them. Characterization of the key dynamics and variables that explain group evolution and functioning is a critical step towards detection, monitoring and, ultimately, control. Key to our success is that results are expressed in the languages of computer science, mathematics, and statistics: novel algorithmic models capable of describing social dynamics; theorems providing limits and guarantees of strategies and control schemes. In this way, social theories of interaction were "coded" in a rigorous setting and analyzed used analytic and simulation tools